Global EFT Interpretation

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TEXAS
The University of Texas at Austin

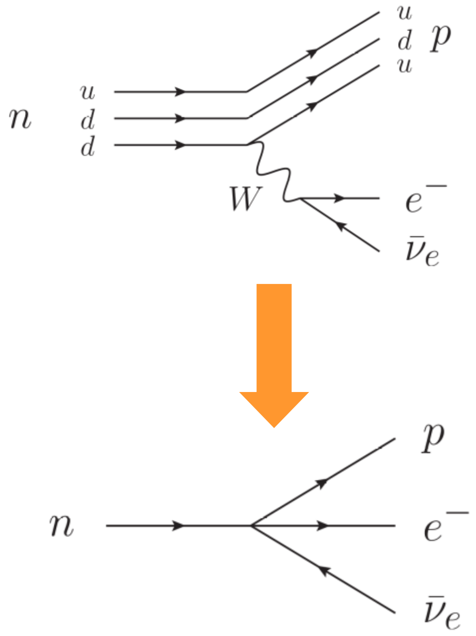
CMS

ATLAS
EXPERIMENT

Why Effective Field Theory?

- Have not yet discovered non-SM particles at the LHC
- But one didn’t need the Sp$\bar{p}$S to discover the weak force: first observation by Becquerel
- Beta decay explained by Fermi with a four-fermion interaction
  - prototype of an effective field theory:
    - generated by “new physics”
    - gives the right answers at nuclear energy scales
    - non-renormalizable dimension 6 operator: theory breaks down at the W mass, at scale ~ $1/\sqrt{G_F}$

Nature on Fermi’s paper:
“speculations too remote from reality to be of interest to the reader”



$$G_F = \frac{1/\sqrt{2}}{v^2}$$

Relevant EFT for LHC

- Standard Model Effective Field Theory (SMEFT): maintain SM gauge invariance, no new light degrees of freedom
  - Higgs is the standard SU(2) doublet
  - No tree-level modification of SM: effects like top FCNC decays enter as higher dimension operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sigma_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sigma_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \dots$$

  - only dimension 5 operator generates neutrino masses & violates lepton number conservation
  - at LHC interesting operators are dimension 6 (or maybe 8)

- Higgs Effective Field Theory (HEFT): treat physical Higgs and Goldstones as independent
  - can express more complex EWSB than SMEFT
  - at the cost of (generically) faster unitarity breakdown
  - often cleaner mapping to Higgs observables, especially interesting for self-coupling
- Weak Effective Field Theory: relevant for B physics observables
  - connect to B anomalies
  - can match to SMEFT via renormalization group running

Complications of SMEFT

- Have to choose a basis of operators (convenience depends on application)
  - “anomalous couplings”: traditional for gauge boson interactions, works with physical Z/γ
  - “Warsaw basis”: uses pre-EWSB gauge boson eigenstates (B/W)
  - “Higgs basis”: gauge mass eigenstates, is a complete basis
  - other options exist – SILH, HISZ – but not much used
  - global fits are in Warsaw basis
- How to handle fermion flavor? (assume generation symmetry or not)
  - without restrictions: 2499 dim-6 operators

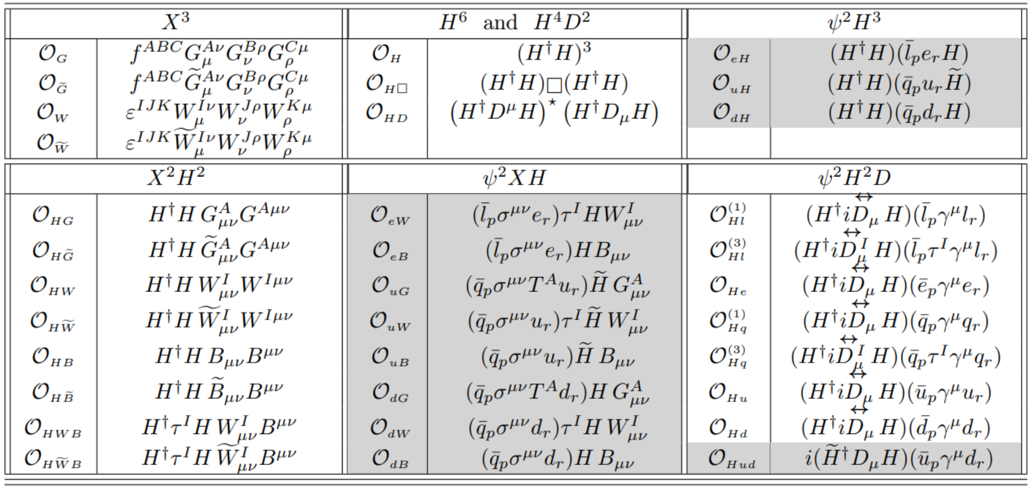
SMEFT Warsaw Basis

gauge boson self-coupling

Higgs self-coupling
(+ wave fcn renormalization)

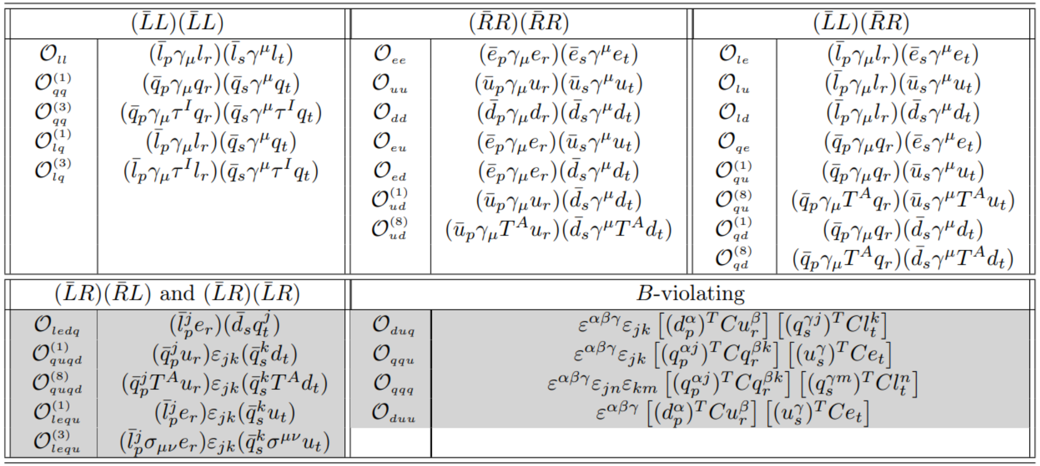
Yukawas

four-fermion operators



X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar l_p e_r H)$
$\mathcal{O}_{\widetilde G}$	$f^{ABC}\widetilde G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
$\mathcal{O}_W$	$\varepsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star (H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar q_p d_r H)$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$



$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$\mathcal{O}_{ll}$	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}^{(1)}_{qq}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$\mathcal{O}^{(3)}_{qq}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$\mathcal{O}^{(1)}_{lq}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}^{(3)}_{lq}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}^{(1)}_{qu}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$\mathcal{O}^{(1)}_{ud}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}^{(8)}_{qu}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$\mathcal{O}^{(8)}_{ud}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$\mathcal{O}^{(1)}_{qd}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$\mathcal{O}^{(8)}_{qd}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar l^j_p e_r)(\bar d_s q^j_t)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^TCu^\beta_r\right]\left[(q^{\gamma j}_s)^TCl^k_t\right]$
$\mathcal{O}^{(1)}_{quqd}$	$(\bar q^j_p u_r)\varepsilon_{jk}(\bar q^k_s d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^TCq^{\beta k}_r\right]\left[(u^\gamma_s)^TCe_t\right]$
$\mathcal{O}^{(8)}_{quqd}$	$(\bar q^j_p T^A u_r)\varepsilon_{jk}(\bar q^k_s T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^TCq^{\beta k}_r\right]\left[(q^{\gamma m}_s)^TCl^n_t\right]$
$\mathcal{O}^{(1)}_{lequ}$	$(\bar l^j_p e_r)\varepsilon_{jk}(\bar q^k_s u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^TCu^\beta_r\right]\left[(u^\gamma_s)^TCe_t\right]$
$\mathcal{O}^{(3)}_{lequ}$	$(\bar l^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q^k_s\sigma^{\mu\nu}u_t)$		

H-gauge boson interactions

Anomalous ff-boson interactions

Expand around SM vacuum, so e.g. can generate apparent "tree" FCNC couplings

$$(H^\dagger H)(\bar q t\tilde H) \to v^2 \bar c t h + \ldots$$

Linear vs Quadratic

- Observables depend on squared amplitudes
  - EFT operators can have effects via interference with SM amplitudes (linear in Wilson coefficients) or directly (quadratic)

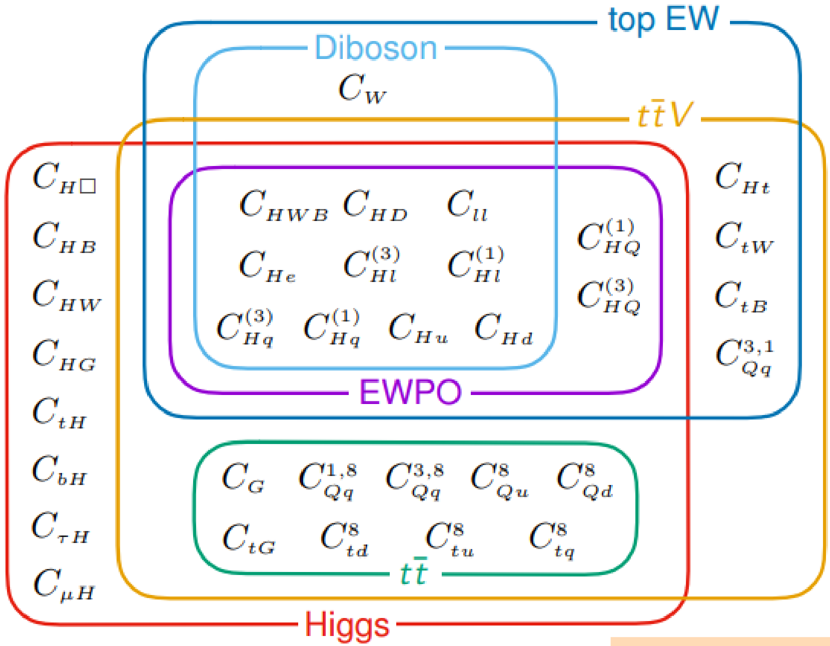
O_i interference with SM O_i direct term O_i-O_j interference

$$\mu = \mu_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} L_i + \sum_i \frac{c_i^2}{\Lambda^4} Q_i + \sum_{i \neq j} \frac{c_i c_j}{\Lambda^4} X_{ij} + \ldots$$

- $1/\Lambda^4$ “quadratic” terms above are formally of same order as dim-8 interference with SM: but have to truncate at some point
- Linear vs quadratic fit results give a sense for truncation systematics

Top vs “other” measurements

- EFT connects precision measurements between many physics sectors
- Connections can be quite subtle!
  - e.g. C_G modifies gluon self coupling and thus $gg \rightarrow t\bar{t}X$
  - C_{tH} modifies $gg \rightarrow HH$ through loops
- top-specific measurements permit breaking flavor degeneracy assumptions



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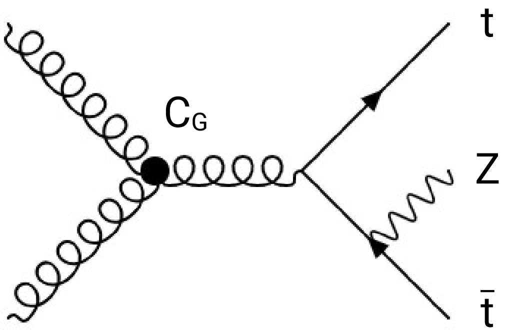
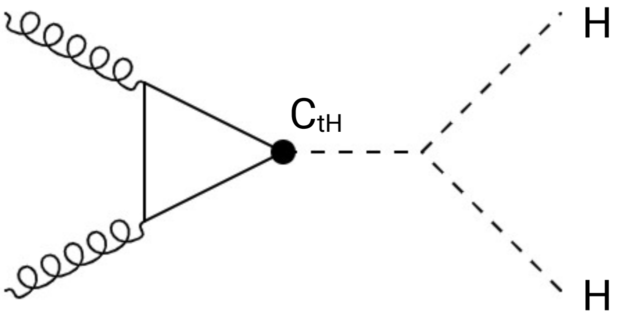
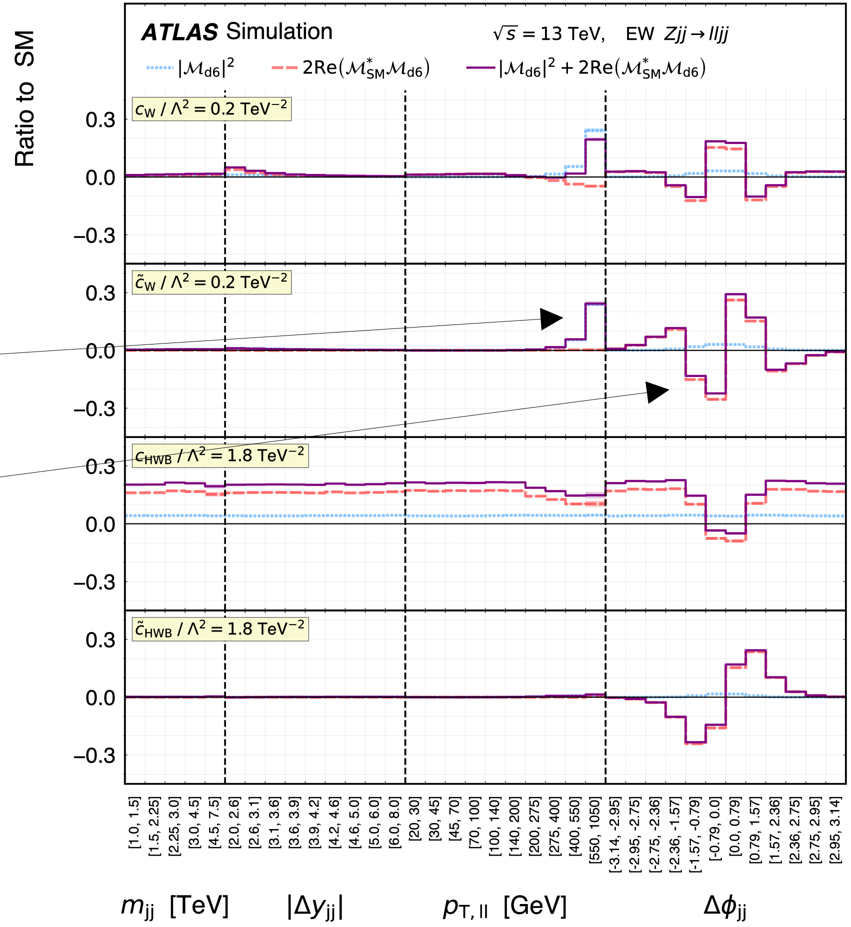




Differential distributions

- Differential distributions play an important role:
  - effects of new operators often increase at higher energy
  - new angular dependencies can arise



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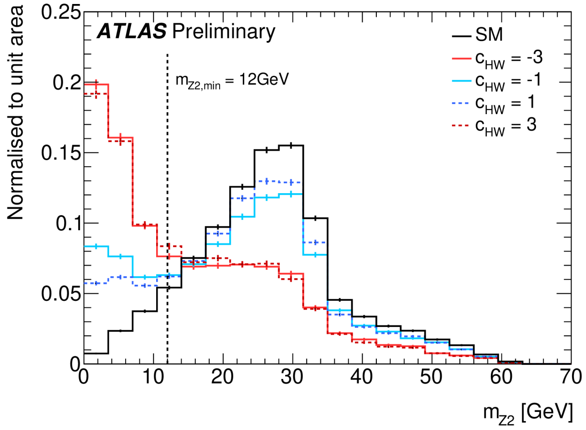
General Issues in EFT Fits

- Processes affected by many operators at once
  - scan one operator at a time? marginalize over all operators?
- Both signal and background are modified
  - potentially by different operators – analyses may be valid for some subset of operators but not for arbitrary basis
  - acceptance/efficiency may be changed for MVA discriminants/unfolded measurements
- Widths, BRs of intermediate states may change
- Quadratic, NLO corrections may be important
  - linear dimension-8 contributions may be at the same level as quadratic dim-6
  - can we predict new physics contributions at same order as SM?
- SM prediction uncertainties (e.g. PDF) can affect similar distributions as EFT operators
- Flat directions not well-constrained by chosen data need to be handled
  - principal component analysis
- Generators may not have exactly the same conventions…



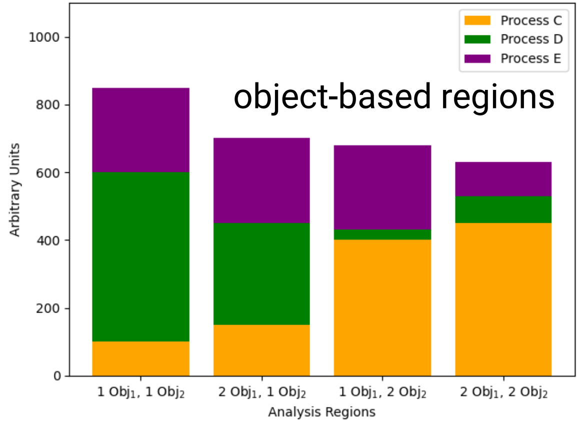
H → 4ℓ kinematics change with nonzero C_{HW}

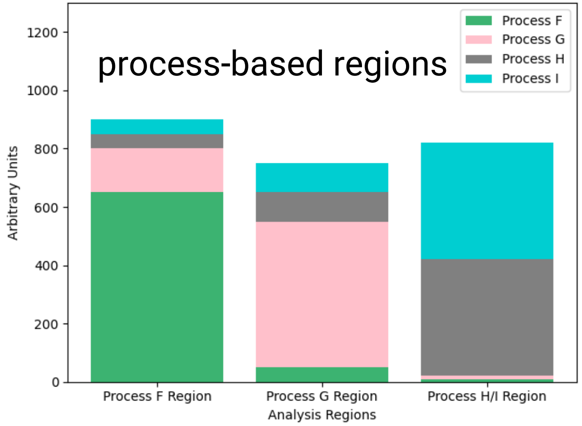
see e.g. CMS, *JHEP 02 (2022) 142* *and talk by Tim Hobbs*

Further discussion in *ATL-PHYS-PUB-2023-030*

General Issues in EFT Fits

- Directly fit detector-level measurements, or unfold to truth level then fit?
  - detector-level is "easy" and great for machine learning but hard to update with better theory – need to be able to rerun analysis with new predictions
  - truth-level differential measurements require care in unfolding and/or definition of fiducial regions
    - this is ~ the Higgs STXS approach (truth regions but shaped by detector constraints)
- Try to disentangle different contributing processes (e.g. ttW vs ttH in multileptons), or take process-inclusive final states?
  - reinterpreting existing measurements that subtract SM-like "background" is complex
  - but repeating analyses for single-process extraction and EFT fits is a hard sell
- For combinations:
  - are inputs statistically independent? Non-trivial even within experiments
  - are systematics (modeling, physics objects, …) consistent?
  - do inputs have consistent EFT validity assumptions?



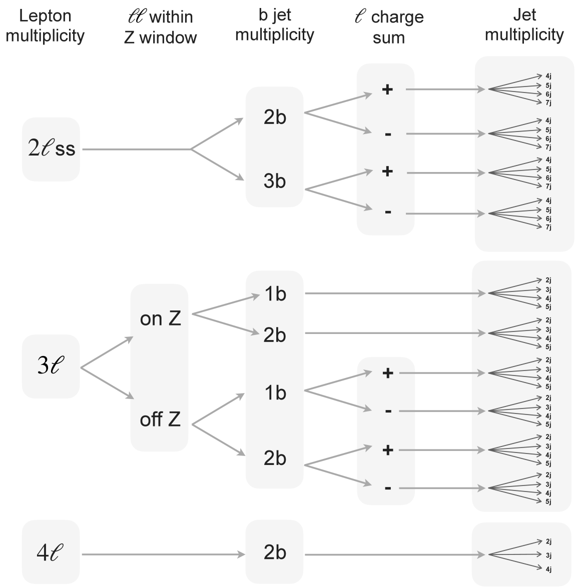


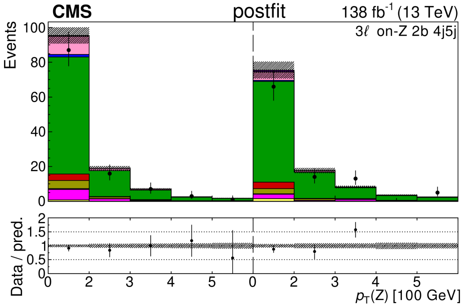
Further discussion in *ATL-PHYS-PUB-2023-030*

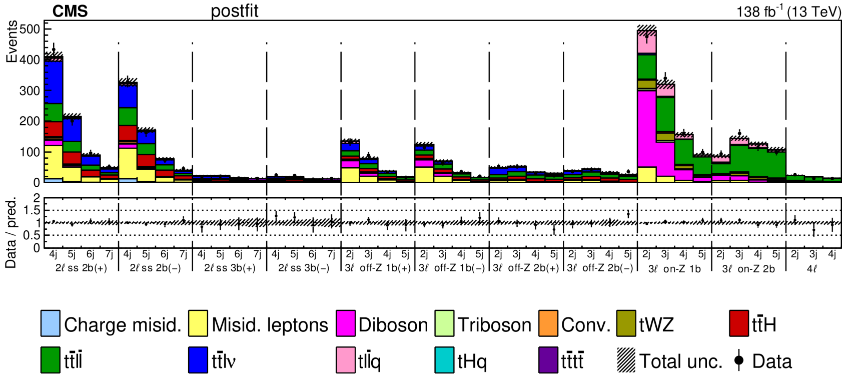
CMS Top Multilepton Fit

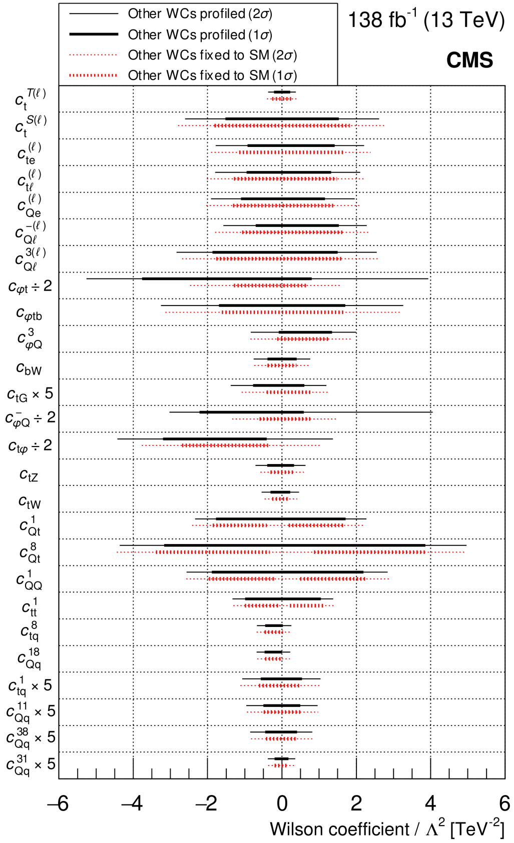
2307.15761
sub. to JHEP

- Coherent analysis of closely related final states
  - dominated by $t\bar{t}$ + X: closely related operators involving top
  - individual MC events reweighted by EFT contributions (multileg LO generation with MLM matching)
  - differential measurements within final states
  - quadratic order for dim-6 operators


Lepton multiplicity
$\ell\ell$ within Z window
b jet multiplicity
ℓ charge sum
Jet multiplicity
2ℓss
2b
3b
+
-
3ℓ
on Z
off Z
1b
2b
4ℓ







YSF talk, Aashwin Basnet

ATLAS Higgs + EW Fit

- Combination of ATLAS Higgs and electroweak data and LEP/SLC electroweak precision observables
  - Higgs STXS production cross sections, decay BRs
  - Diboson differential measurements, VBF Z production
- Test both linear and quadratic fits
- Some corrections needed for operator effects on backgrounds, H → 4l mass distribution

Higgs

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	$\mathrm{ggF}, \mathrm{VBF}, WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ^*$	$\mathrm{ggF}, \mathrm{VBF}, WH, ZH, t\bar{t}H\,(4\ell)$	139
$H \to WW^*$	$\mathrm{ggF}, \mathrm{VBF}$	139
$H \to \tau\tau$	$\mathrm{ggF}, \mathrm{VBF}, WH, ZH, t\bar{t}H\,(\tau_{\mathrm{had}}\tau_{\mathrm{had}})$	139
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139

Diboson

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55\,GeV$, $p_{\mathrm{T}}^{\mathrm{jet}} < 35\,GeV$	$p_{\mathrm{T}}^{\mathrm{lead.\ lep.}}$	36
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)\,GeV$	m_{T}^{WZ}	36
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	$m_{4\ell} > 180\,GeV$	m_{Z2}	139
$pp \to \ell^{+}\ell^{-}jj$	$m_{jj} > 1000\,GeV$, $m_{\ell\ell} \in (81, 101)\,GeV$	$\Delta\phi_{jj}$	139

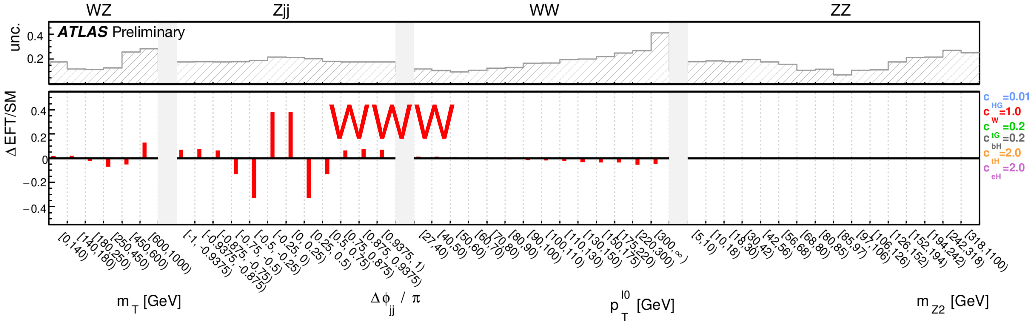
EWPO

Observable
Γ_Z [MeV]
R_{ℓ}^{0}
R_{c}^{0}
R_{b}^{0}
$A_{\mathrm{FB}}^{0,\ell}$
$A_{\mathrm{FB}}^{0,c}$
$A_{\mathrm{FB}}^{0,b}$
$\sigma_{\mathrm{had}}^{0}$ [pb]

ATLAS-PHYS-PUB-2022-037

ATLAS Higgs + EW: Impacts

Some examples of operator effects on observables…

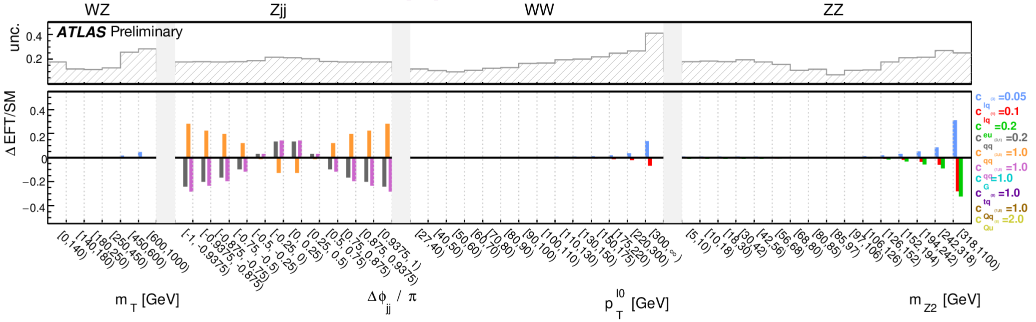


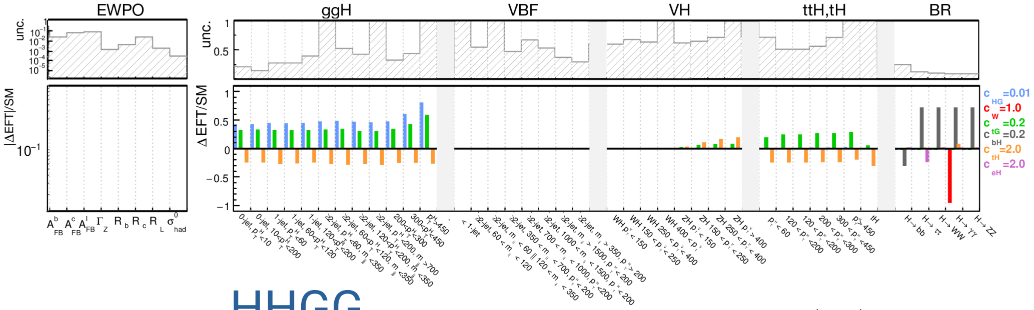
WWW

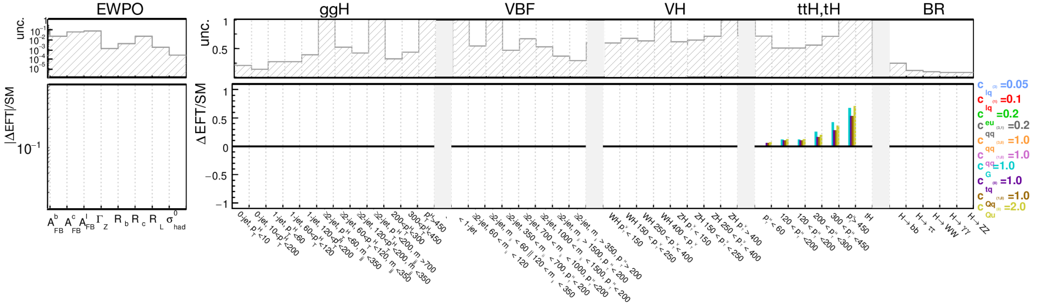
qqll qqll

uuee

qqqq qqqq ttqq







HHGG

ttHG

(v^2)ttH

(v^2)bbH

GGG

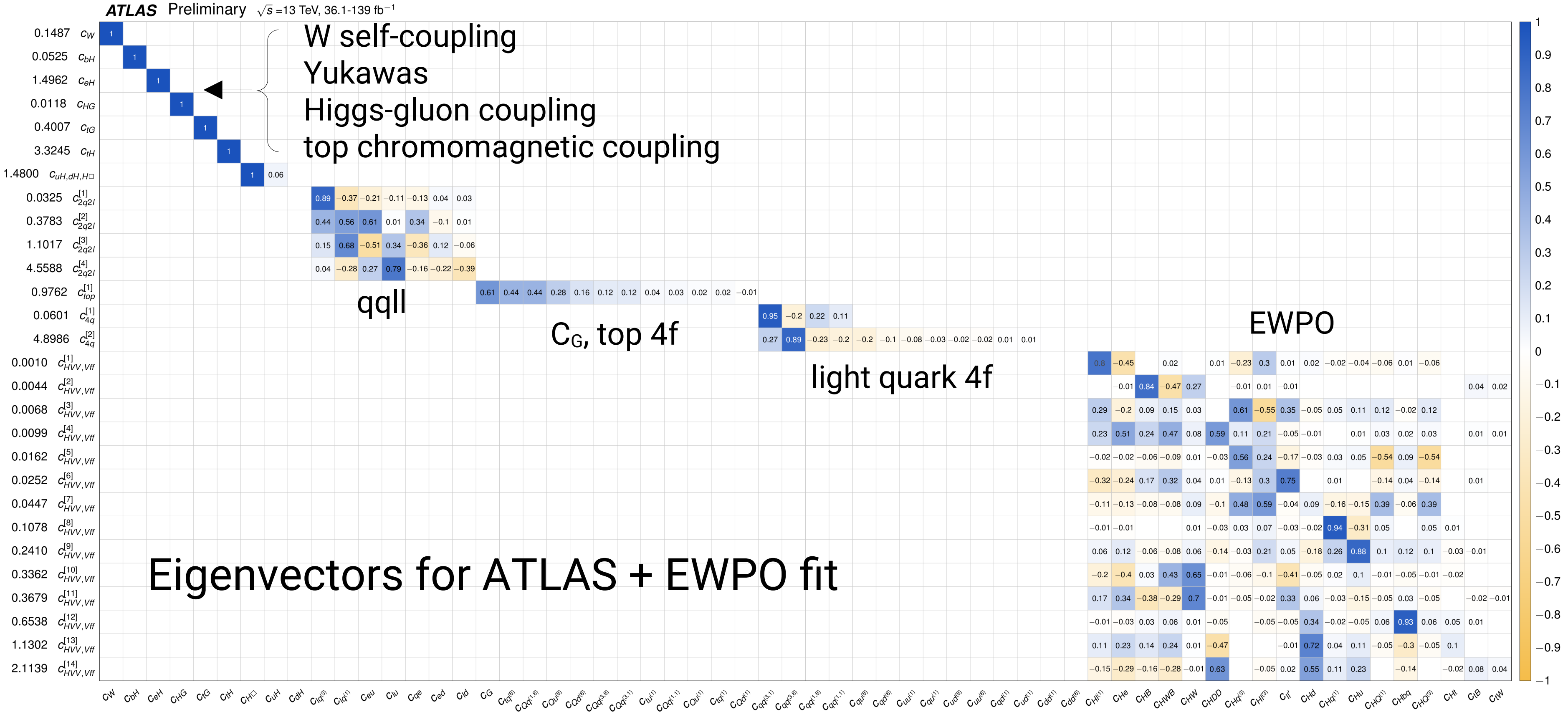
ttqq

QQqq

QQuu

ATLAS Higgs + EW: Basis

- Use eigenvector decomposition to avoid large correlations between operator constraints



W self-coupling
Yukawas
Higgs-gluon coupling
top chromomagnetic coupling

qqll

C$_G$, top 4f

light quark 4f

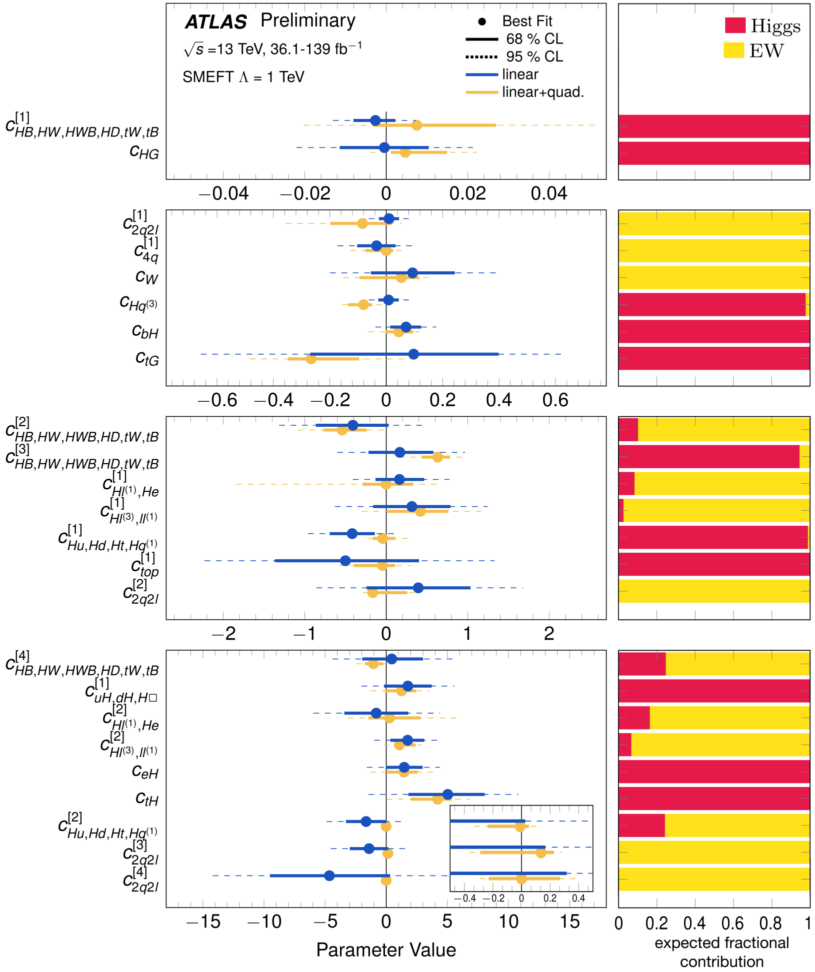
EWPO

Eigenvectors for ATLAS + EWPO fit

ATLAS Higgs + EW: Results

- ATLAS-only results shown here
  - also have ATLAS + EWPO
- Consistent with no new physics
- Do both linear and quadratic fits
  - in some cases qualitatively quite different

ATLAS-PHYS-PUB-2022-037



~ NP Scale

\> 5 TeV

\> 2 TeV

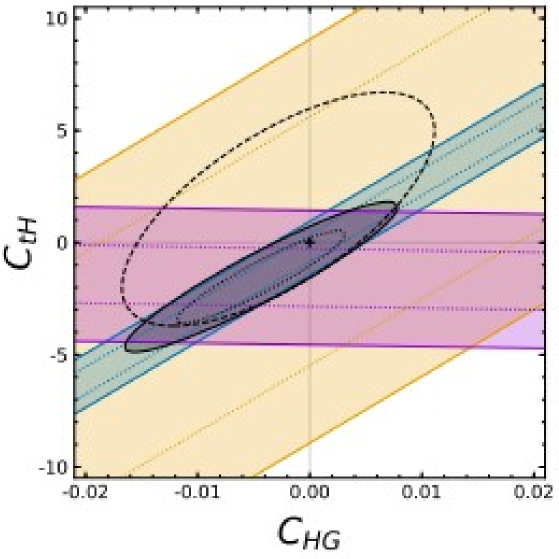
\> 1 TeV

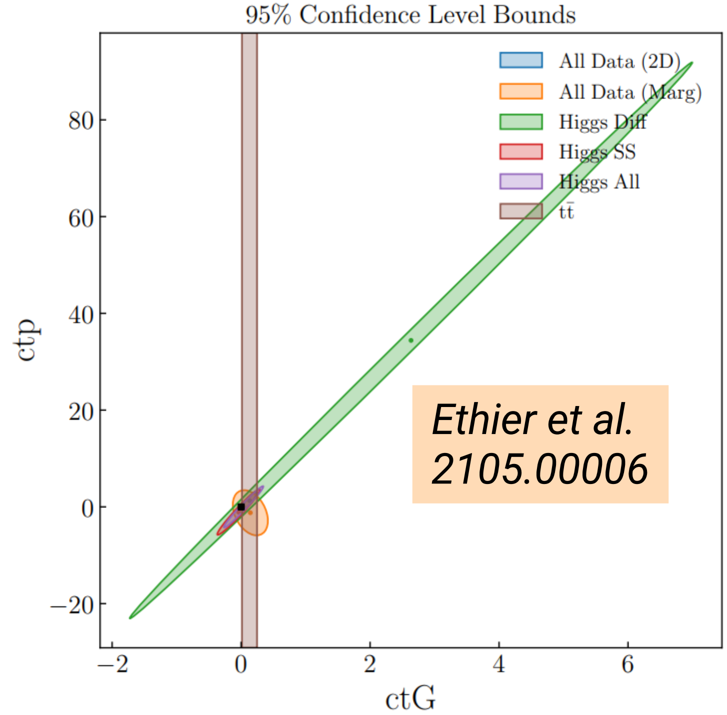
\> 0.4 TeV

Fully Global Fits

- Fits including LHC data + EWPO (either directly included in fits or as operator constraints)
- Complementarity of top and Higgs measurements in fits

Ellis et al.
2012.02779



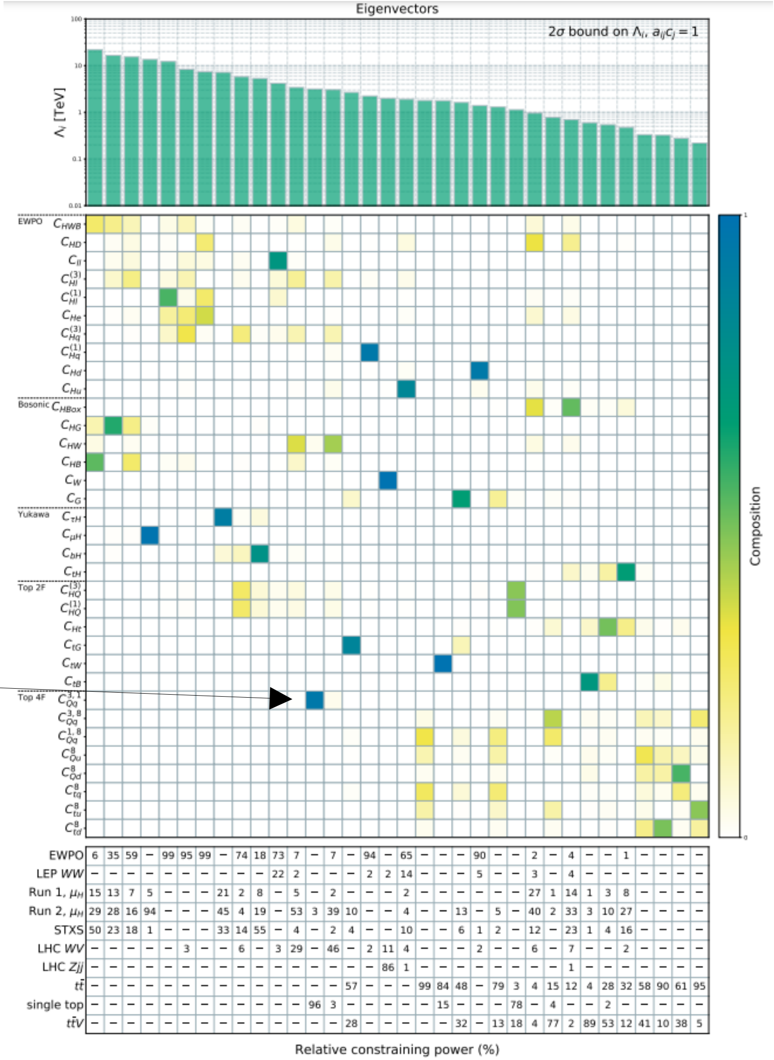


Ethier et al.
2105.00006

Global Fit: Takeaways

- Constraints on new physics scales range from ~ 200 GeV to > 20 TeV
- Interplay between top and Higgs measurements
  - not so much top and EWPO
- Constraints from top measurements in the 200 GeV to 3 TeV range
  - strongest single constraint is a four-fermion operator from single top

Ellis et al.
2012.02779



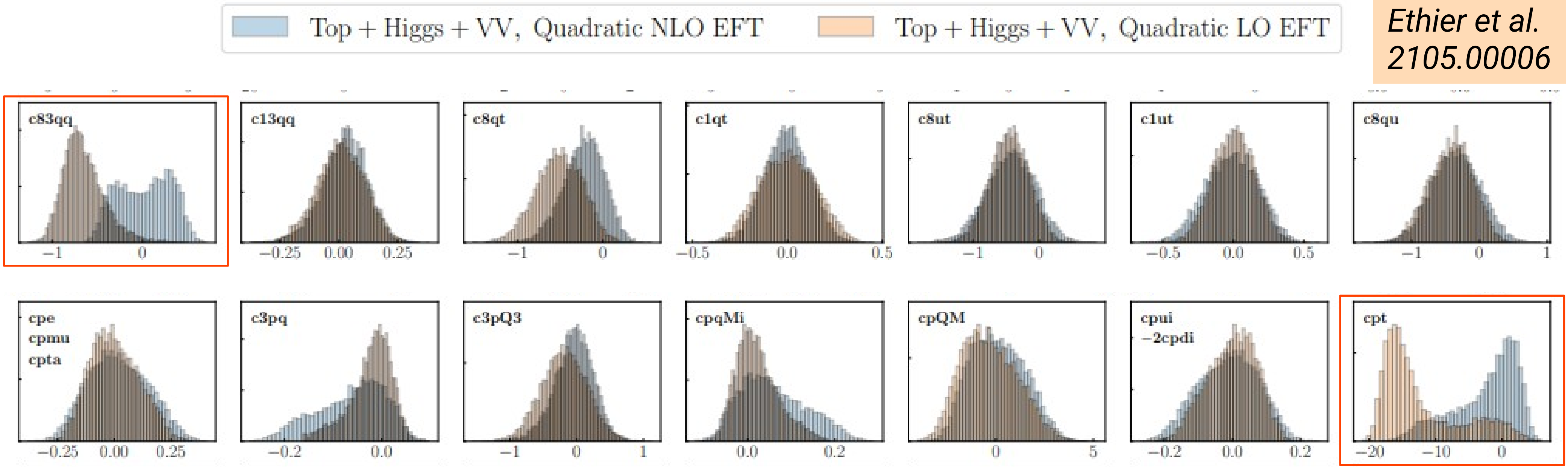
EWPO	6	35	59	–	99	95	99	–	74	18	73	7	–	7	–	94	–	65	–	–	–	90	–	–	2	–	4	–	–	1	–	–	–	–
LEP WW	–	–	–	–	–	–	–	–	–	–	22	2	–	–	–	2	2	14	–	–	–	5	–	–	3	–	4	–	–	–	–	–	–	–
Run 1, μ_H	15	13	7	5	–	–	–	21	2	8	–	5	–	2	–	–	–	2	–	–	–	–	–	–	27	1	14	1	3	8	–	–	–	–
Run 2, μ_H	29	28	16	94	–	–	–	45	4	19	–	53	3	39	10	–	–	4	–	–	13	–	5	–	40	2	33	3	10	27	–	–	–	–
STXS	50	23	18	1	–	–	–	33	14	55	–	4	–	2	4	–	–	10	–	–	6	1	2	–	12	–	23	1	4	16	–	–	–	–
LHC WV	–	–	–	–	–	3	–	–	6	–	3	29	–	46	–	2	11	4	–	–	–	2	–	–	6	–	7	–	–	2	–	–	–	–
LHC Zjj	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	86	1	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–
$t\bar{t}$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	57	–	–	–	99	84	48	–	79	3	4	15	12	4	28	32	58	90	61	95
single top	–	–	–	–	–	–	–	–	–	–	–	–	96	3	–	–	–	–	–	15	–	–	–	78	–	4	–	–	2	–	–	–	–	–
$t\bar{t}V$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	28	–	–	–	–	–	32	–	13	18	4	77	2	89	53	12	41	10	38	5

Relative constraining power (%)

NLO Impact on Fits

- Compare global fits with NLO corrections on and off
- Significant differences seen for some operator fits – more consistent with SM

Ethier et al.
2105.00006

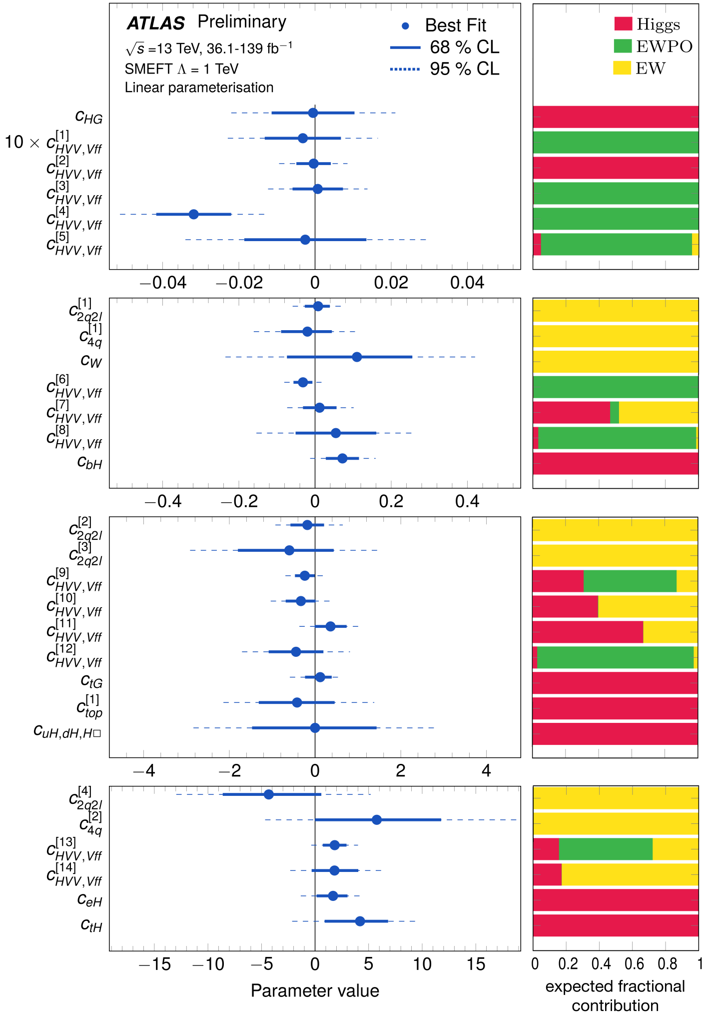


Future Directions for Global Fits

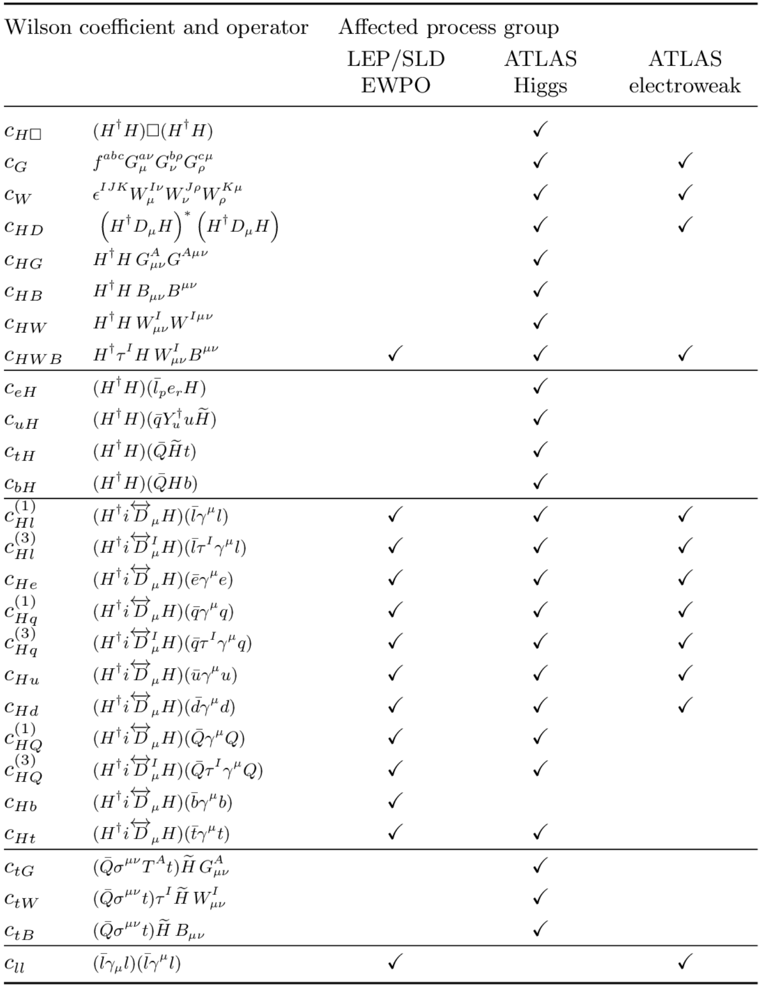
- Being able to do fully global analyses requires coherent treatments of signals + backgrounds
  - preferably built-in to analyses to begin with, not added post hoc
  - flavor assumptions need some care
- Theory refinement:
  - NLO for EFT contributions
  - Handling truncation + EFT validity assumptions
  - Combination with flavor data
- Add & optimize observables
  - NP scale limits go as $1/\sqrt{C_i}$ while in many cases C_i constraints can be expected to go as $\sqrt{\text{Lumi}}$
  - potentially great benefits from new channels + additional differential distributions
  - Engineer better observables with machine learning
- Maximum preservation of information from analyses will be important
  - Ability to rerun analyses with updated generators? Unfolded results?

Extra

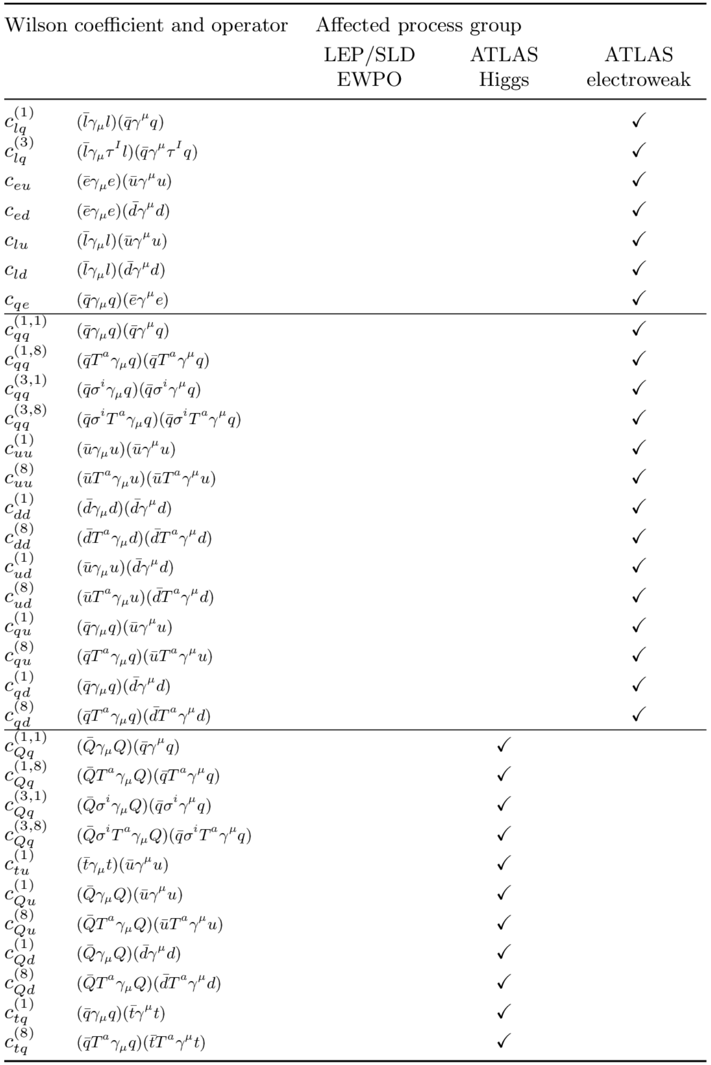
ATLAS Higgs + EW + EWPO Result



ATLAS Higgs + EW Operator Effects

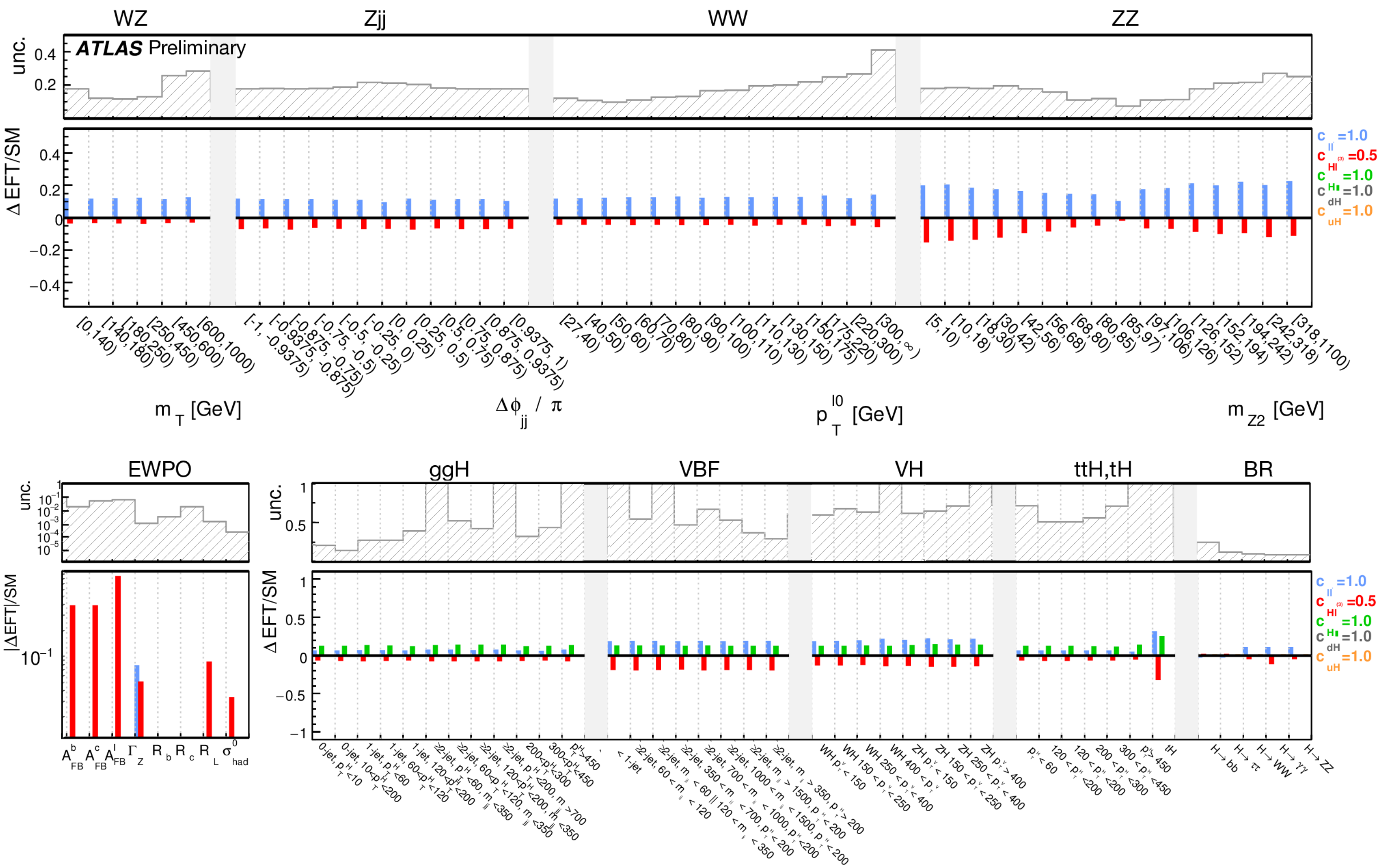


Wilson coefficient and operator		Affected process group		
		LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		✓	
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$		✓	✓
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$		✓	✓
c_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$		✓	✓
c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$		✓	
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		✓	
c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$		✓	
c_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	✓	✓	✓
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$		✓	
c_{uH}	$(H^\dagger H)(\bar{q} Y_u^\dagger u \widetilde{H})$		✓	
c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H} t)$		✓	
c_{bH}	$(H^\dagger H)(\bar{Q} H b)$		✓	
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	✓	✓	✓
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	✓	✓	
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$	✓	✓	
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	✓		
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	✓	✓	
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\, G_{\mu\nu}^A$		✓	
c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\widetilde{H}\, W_{\mu\nu}^I$		✓	
c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\widetilde{H}\, B_{\mu\nu}$		✓	
c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓		✓



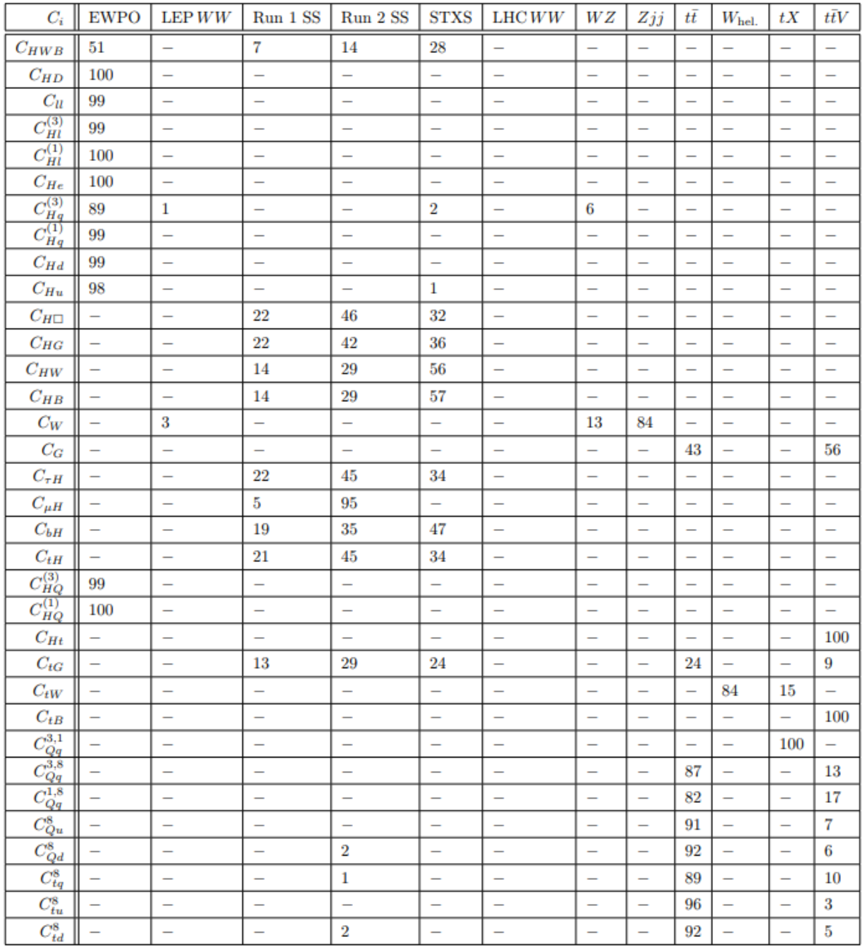
Wilson coefficient and operator		Affected process group		
		LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$			✓
$c_{lq}^{(3)}$	$(\bar{l}\gamma_\mu\tau^I l)(\bar{q}\gamma^\mu\tau^I q)$			✓
c_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$			✓
c_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$			✓
c_{lu}	$(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$			✓
c_{ld}	$(\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)$			✓
c_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$			✓
$c_{qq}^{(1,1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$			✓
$c_{qq}^{(1,8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$			✓
$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$			✓
$c_{qq}^{(3,8)}$	$(\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$			✓
$c_{uu}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$			✓
$c_{uu}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$			✓
$c_{dd}^{(1)}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$			✓
$c_{dd}^{(8)}$	$(\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$			✓
$c_{ud}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$			✓
$c_{qu}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$			✓
$c_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$			✓
$c_{qd}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$		✓	
$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$		✓	
$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$		✓	
$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$		✓	
$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$		✓	
$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$		✓	
$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$		✓	
$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$		✓	
$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$		✓	
$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$		✓	
$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$		✓	

ATLAS Higgs + EW: Impacts



Constraining Power

- In practice different operator sectors are constrained by different classes of measurements
- C_{tG} main overlap between Higgs and top measurements



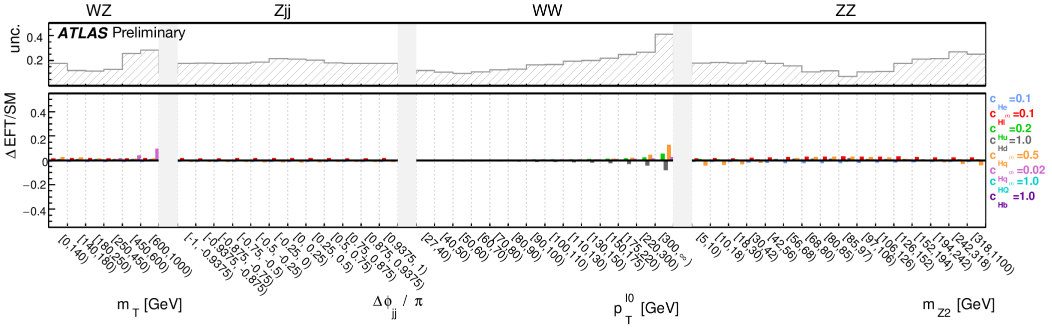
C_i	EWPO	LEP WW	Run 1 SS	Run 2 SS	STXS	LHC WW	WZ	Zjj	$t\bar{t}$	$W_{\text{hel.}}$	tX	$t\bar{t}V$
C_{HWB}	51	–	7	14	28	–	–	–	–	–	–	–
C_{HD}	100	–	–	–	–	–	–	–	–	–	–	–
C_{ll}	99	–	–	–	–	–	–	–	–	–	–	–
$C_{Hl}^{(3)}$	99	–	–	–	–	–	–	–	–	–	–	–
$C_{Hl}^{(1)}$	100	–	–	–	–	–	–	–	–	–	–	–
C_{He}	100	–	–	–	–	–	–	–	–	–	–	–
$C_{Hq}^{(3)}$	89	1	–	–	2	–	6	–	–	–	–	–
$C_{Hq}^{(1)}$	99	–	–	–	–	–	–	–	–	–	–	–
C_{Hd}	99	–	–	–	–	–	–	–	–	–	–	–
C_{Hu}	98	–	–	–	1	–	–	–	–	–	–	–
$C_{H\Box}$	–	–	22	46	32	–	–	–	–	–	–	–
C_{HG}	–	–	22	42	36	–	–	–	–	–	–	–
C_{HW}	–	–	14	29	56	–	–	–	–	–	–	–
C_{HB}	–	–	14	29	57	–	–	–	–	–	–	–
C_W	–	3	–	–	–	–	13	84	–	–	–	–
C_G	–	–	–	–	–	–	–	–	43	–	–	56
$C_{\tau H}$	–	–	22	45	34	–	–	–	–	–	–	–
$C_{\mu H}$	–	–	5	95	–	–	–	–	–	–	–	–
C_{bH}	–	–	19	35	47	–	–	–	–	–	–	–
C_{tH}	–	–	21	45	34	–	–	–	–	–	–	–
$C_{HQ}^{(3)}$	99	–	–	–	–	–	–	–	–	–	–	–
$C_{HQ}^{(1)}$	100	–	–	–	–	–	–	–	–	–	–	–
C_{Ht}	–	–	–	–	–	–	–	–	–	–	–	100
C_{tG}	–	–	13	29	24	–	–	–	24	–	–	9
C_{tW}	–	–	–	–	–	–	–	–	–	84	15	–
C_{tB}	–	–	–	–	–	–	–	–	–	–	–	100
$C_{Qq}^{3,1}$	–	–	–	–	–	–	–	–	–	–	100	–
$C_{Qq}^{3,8}$	–	–	–	–	–	–	–	–	87	–	–	13
$C_{Qq}^{1,8}$	–	–	–	–	–	–	–	–	82	–	–	17
C_{Qu}^{8}	–	–	–	–	–	–	–	–	91	–	–	7
C_{Qd}^{8}	–	–	–	2	–	–	–	–	92	–	–	6
C_{tq}^{8}	–	–	–	1	–	–	–	–	89	–	–	10
C_{tu}^{8}	–	–	–	–	–	–	–	–	96	–	–	3
C_{td}^{8}	–	–	–	2	–	–	–	–	92	–	–	5

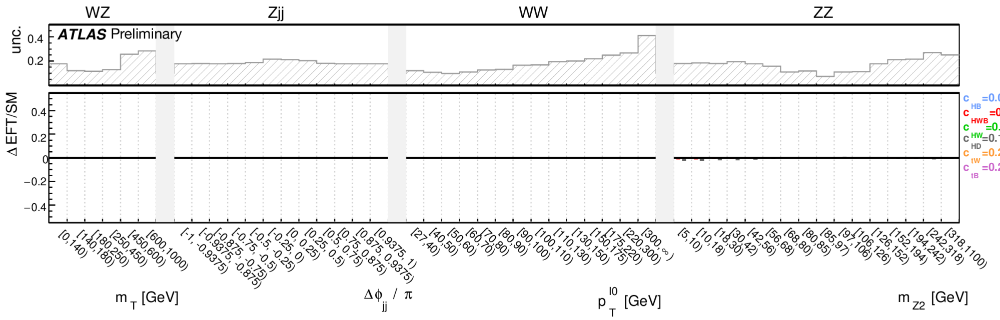
Table 7. *Relative constraining power in percent of different datasets on each coefficient of the global fit individually. Entries below 1% are not displayed. 'SS', $W_{hel.}$ and tX refer to Higgs signal strength, W-helicity fraction and single top data, respectively.*

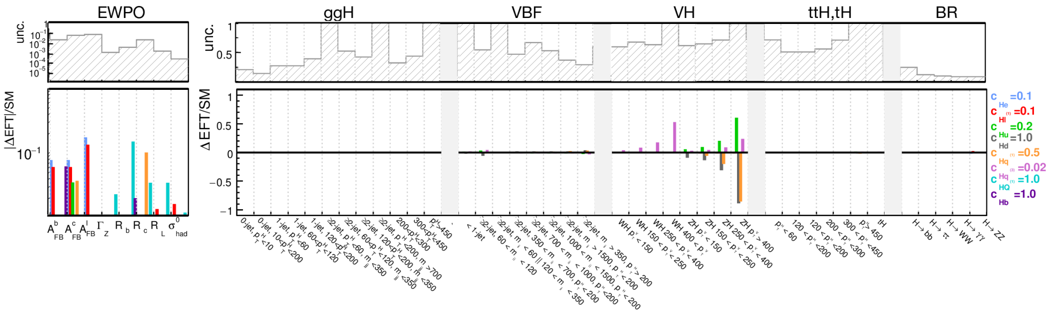
2012.02779

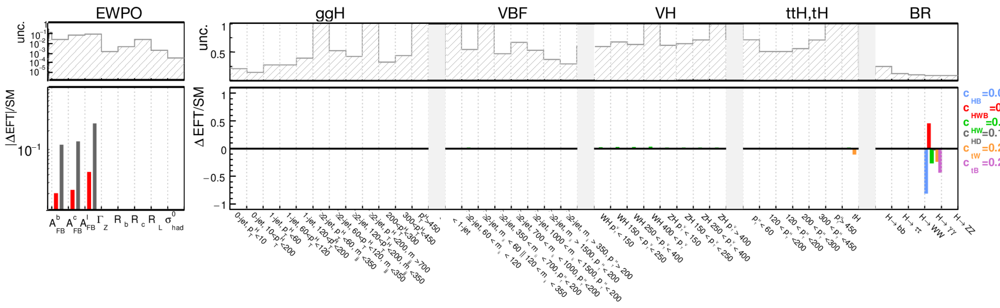
ATLAS Higgs + EW: Impacts

HHll









HHqq

HHdd

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